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*A number of astrophysical systems involve radiative shocks that collapse spatially in response to energy lost through radiation. Supernova remnants are an example of systems that cool enough to radiatively collapse. This is believed to produce thin, dense shells that are Vishniac unstable. This type of instability may be responsible for the convoluted structure of supernova remnants such as the Cygnus Loop. We are conducting experiments on the Omega laser intended to produce such collapsing shocks and to study their evolution. The experiments use the laser to accelerate a thin slab of driving material (beryllium) through 1.1 ATM of argon gas (~2 mg/cc) at ~100 km/sec. The simulations also predict that the dense layer will be pushed ahead of the dense beryllium by the leading edge of the expansion of this material. The experiment is diagnosed in two ways. X-ray radiography has detected the presence of the dense shocked layer. These data indicate that the shock velocity is ~100 km/s. A unique, side-on application of the VISAR (Velocity Interferometer System for Any Reflector) technique is used to detect frequency shifts from ionization and any reflections from the edge of the dense shocked layer.*


## I. INTRODUCTION

Laboratory astrophysics is constantly adapting to explore new physical systems. The experiments discussed here are an attempt to enter the regime of collapsing radiative shocks. Whenever a fast enough astrophysical shock traverses a dense enough medium, the shocked region may radiatively collapse into a thin layer and be subject to thin-layer instability. This appears to happen as blast waves emerge from supernovae[1] and in supernova remnants with dense enough circumstellar environments or structures. In addition, all supernova remnants eventually cool enough to radiatively collapse[2] due to the negative slope of the cooling rate between temperatures of order 10 eV and 1 keV. The extremely convoluted structure of the Cygnus Loop is a good example. This motivates experiments to explore this dynamic regime. Previous experiments focused on radiative shocks have included the observation of radiative precursors in systems that did not include[3] and may have included[4,5] a collapsed layer, and the observation of structure in systems[6,7] in which electron heat transport provided the energy that was radiated.

The Vishniac instability[8,9] provides additional motivation for such experiments. Thin enough shells driven by internal pressure are unstable to this mechanism. Prior laboratory experiments have not previously addressed the astrophysical regime where the shell collapses by post-shock radiative cooling. They have examined blast-wave-driven systems in which substantial energy must be invested in ionization and radiation during the shock transition, and which have a correspondingly low effective adiabatic index. The observation of structure in xenon but not in nitrogen has been attributed to this process.[10,11]

Using the Omega laser, we are working to produce a planar collapsed shock using gas filled targets. As the experiment progresses, we hope to investigate the affects of the Vishniac instability on the structure and evolution of this layer.

## II. EXPERIMENT

Gas filled targets (see Figure 1) were constructed mainly from beryllium, with the main target body .6 mm ID, .9 mm OD, and 3 mm long. Drive lasers focused to a 820 mm diameter (FWHM) spot on a 50 um thick, 2.5 mm diameter beryllium washer, while a lead-doped plastic washer slowed the shocked material outside of the shock tube radius, to help protect diagnostics. A tin area backlighter provided the necessary illumination for radiography using x-ray framing cameras. A gold grid was placed on the target as a spatial indicator for radiography. Beryllium arms distanced quartz windows from the plasma, and provided a path through the gas perpendicular to the shock propagation direction for the VISAR (Velocity Interferometer System for Any Reflector) diagnostic. These arms were located towards the back end of the target, away from the drive washer, and protected from high-energy electrons

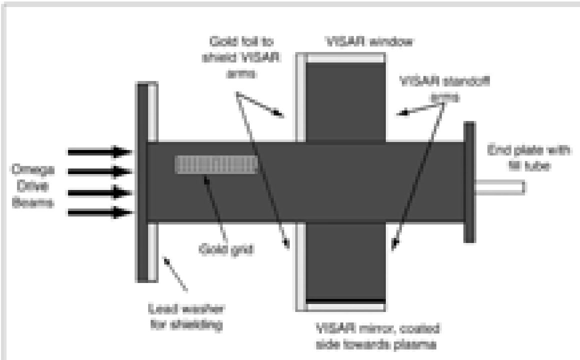


**Figure 1: Target diagram. The long dimension of the target is 3 mm, while the drive washer is 2.5 mm in diameter. The Sn backlighter foil is not shown in the picture, and would be situated directly behind the target.**

with gold foil. The quartz component closest to the interferometer laser was clear quartz, while the opposite component had one side coated with 100 nm aluminum, to provide the reflection of the interferometer beam back onto itself.

On the target, 10 drive lasers at 400-500 J each were focused on the drive washer in a 1 ns square pulse. This launched a shock down the length of the target through the argon gas. At a later time, 7 beams at 400 J each focused on the backlighting material for side-on radiography. The radiographic diagnostic used 16 pinholes to image x-rays from the large-area source onto a gated framing camera with 8x magnification. The shock and collapsed layer should be apparent as dark absorption features on the x-ray images.

The side-on VISAR diagnostic used a .532 um laser interferometer, shone through the argon gas perpendicular to the direction of propagation of the shock. As the density of the electrons increased in front of the shock, fringe shifts should have been detected as a result of the changing optical path length through the gas. From the fringe shift data, the density as a function of time of the electrons should have been apparent until the signal was lost to collisional absorption, as the shock neared the interferometer path. The target was oriented in space such that it was perpendicular to the lines of sights of both diagnostics.

The application of a VISAR diagnostic to measure density as a function of time is unique; such diagnostics are more often used to measure the speed of a reflecting surface. Fundamentally, the VISAR system converts frequency shifts to fringe shifts, unlike ordinary interferometers that convert optical path differences to shift shifts. Thus, such a system can measure any process that creates frequency shifts, including plasma formation. The way this works is as follows.

The intensity pattern of the fringe shifts is given by $I = E^* E$ where

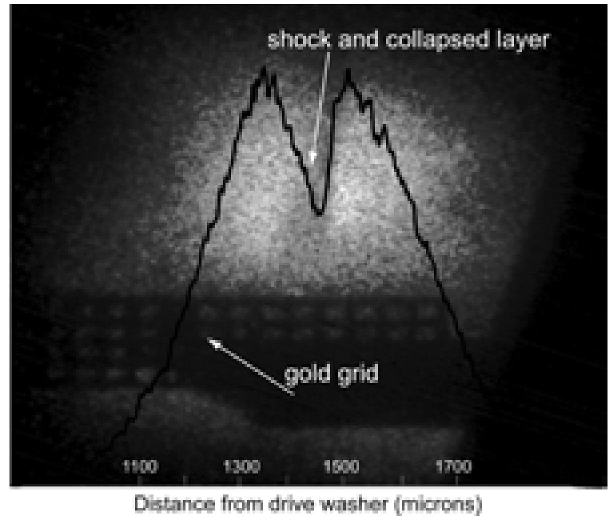


**Figure 2: Radiography of shock in argon, with gold grid and dense shock and layer labeled.**

$$E = E_L e^{-i(\Omega y + \phi_L)} + E_s e^{-i(-\Omega y + \phi_s)}. \tag{1}$$

The parameters $\Omega$ and $y$ describe an initial tilt to the output beam splitter, $\phi_s$ refers to the optical path of the short arm through the plasma of the interferometer, while $\phi_L$ refers to the optical path of the long arm through the plasma. The long arm passes through a delay ($\tau$) and then through the plasma, and so

$$\phi_s(t) = \int_0^t \frac{d\phi_n}{dt}\Big|_{t'} dt' \tag{2a}$$

$$\phi_L(t) = \int_0^t \frac{d\phi_n}{dt}\Big|_{t'-\tau} dt' \tag{2b}$$

The time t = 0 is arbitrarily set to before the phase of the light is shifted. In this case, the optical path (in wavelengths) through the plasma is

$$\phi_n = \frac{L}{\lambda} = \frac{kL}{2\pi} = \frac{\omega L}{2\pi v_\phi} = \frac{\omega L}{2\pi c}\sqrt{1 - \frac{n}{n_c}} \tag{3}$$

where $L$ is the distance traveled through the plasma, $\lambda$ is the wavelength of the light, $\omega$ is the incident frequency, $c$ is the speed of light, $v_\phi$ is the phase velocity of light in the plasma, $n$ is the electron density, and $n_c$ is the critical density. [12]

The frequency shift due to a change in density is

$$\frac{d\phi_n}{dt} = \frac{L}{2\lambda}\frac{1}{\sqrt{1 - n(t)/n_c}}\frac{1}{n_c}\frac{dn(t)}{dt} \tag{4}$$

Substitute equation (4) into the expression for $\phi_L$ (equation (2)) to get the shift in fringe intensity. This can also be expressed in number of fringes as a function of time as

$$\Delta\Phi(t) = 2\pi \frac{dn(t=0)}{\lambda n_c}[n_e(t-\tau) - n_e(t)]. \tag{5}$$

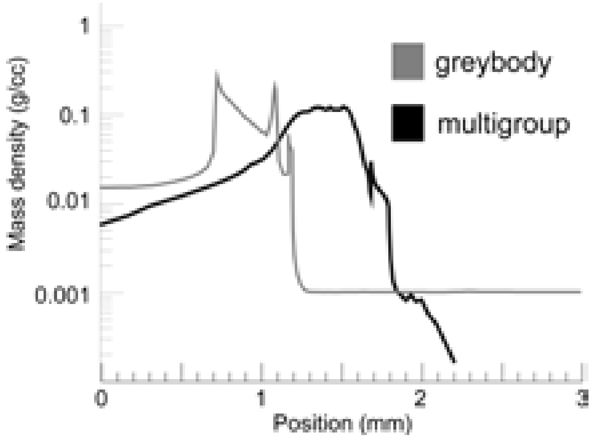


**Figure 3: Initial greybody simulations showed a dense, thick, collapsed layer in argon. Subsequent multigroup simulations, which better account for radiation effects, show that the collapsed layer is not as significant as originally thought.**

## III. RESULTS

Radiography in argon showed some evidence of a collapsed layer in front of the shock (see Figure 2), but of lower apparent density than a greybody simulation predicted. This alone could be due to the alignment of the shock and the diagnostic line of sight, or to the non-planarity of the shock. However, a multigroup simulation, which ought to be more accurate, gave different results, showing that the shocked layer in the argon was less dense and was not separated from the dense Be material, as shown in Figure 3.

It is clear from the x-ray transmission profile that there is a narrow layer of argon. Comparison to the gold grid gives the thickness of the layer to be approximately 50 um, and position with respect to the grid gives a shock velocity of approximately 110 km/sec. The ratio of the intensity of the lineout in the shocked area to the unshocked area gives a density of approximately 10 kg/m$^3$ (10 mg/cc).

A total of approximately 10 shots have been diagnosed using the side-on VISAR method, in both argon and xenon-filled targets. Fringes were always detected until the laser fired, but typically the signal vanished during the laser pulse, which we will discuss shortly. The signal reappeared briefly approximately 15 ns seconds later, which corresponds to the time when the shocked layer detected by the radiography passes through the VISAR line of sight. We attribute these late signals to reflection from the dense, shocked layer. We did in one case also observe signals at the beginning of the laser pulse long enough to see some shifting of the fringes, as is shown in Figure 4. The simulated results for different

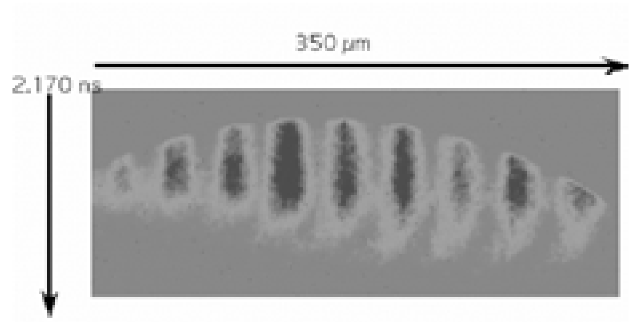


**Figure 4: Fringe shift data from VISAR. We attribute the early loss of signal to collisional absorption as the result of preheat.**

transverse lengths are shown in Figure 5, and seem to overestimate the electron density by an order of magnitude by 0.5 ps after fringe shifts begin.

In most of the VISAR data, the loss of signal during the laser pulse was very likely the consquence of preheat. While the electron preheat is not known, the implications of the radiative preheat predicted by simulations are as follows. According to results of simulations, at one nanosecond Te ≈ .015 keV, and $Z_{eff}$ ≈5. For attenuation due to collisional absorption,

$$\kappa = \frac{\nu_{ei}}{c} \frac{n_e / n_c}{\sqrt{1 - n_e / n_c}} cm^{-1}$$

where

$$\nu_{ei} = 9x10^{-11} n Z_{eff} \ln \Lambda / T_{keV}^{1.5}$$

and

$$n_c = 1.1 \times 10^{21} \Big/ \lambda_\mu^2 = 3.9 \times 10^{21} cm^{-3}.$$

For our system, ln $\Lambda \approx 20$. At early times, the density should still be the background density times $Z_{eff}$, $n_e = 1.375 \times 10^{20} cm^{-3}$.

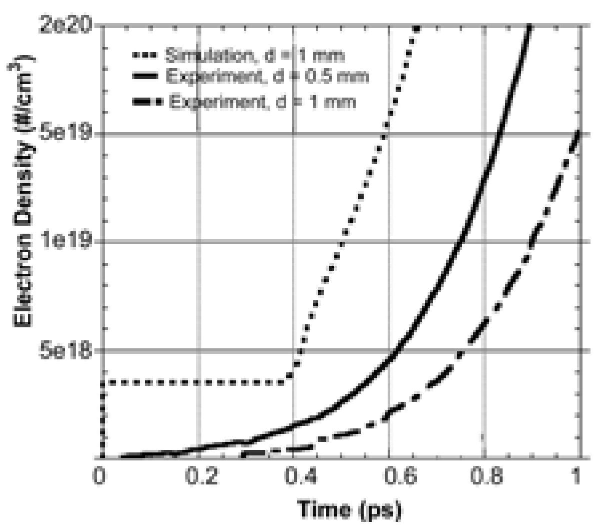


**Figure 5: Results of simulations vs. experimental data, assuming different plasma sizes d = 0.5 mm and 1 mm. The simulation appears to overestimate the electron density, at least in this case.**

These parameters give an absorption coefficient of $\kappa = 73\ cm^{-1}$, or a mean free path of 140 um. To reach the detector, the beam must travel over a millimeter, so it is not surprising that by one nanosecond we will have lost the interferometer beam due to collisional absorption.

## IV. CONCLUSIONS AND FUTURE DIRECTIONS

Initial experiments using side-on x-ray radiography were successful at imaging the shock and collapsed layer. Multigroup simulations indicated that argon is not the ideal fill gas for the targets, as the collapsed layer is neither as dense as desired nor is it separated from the dense Be. Xenon is predicted to be a much better fill gas to achieve both these goals, and will be used in further experiments. Such experiments will use a vanadium backlighter, in a backlit-pinhole configuration to improve the signal-to-noise ratio in radiographic images.

## V. ACKNOWLEGDEMENTS

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## VI. REFERENCES

[1] ENSMAN, L and A. BURROWS. "Shock Breakout in SN 1987a", *Ap. J.*, **393,** 10 July, p. 742 (1992).

[2] BLONDIN J.M., E.B. WRIGHT, K.J. BORKOWSKI, and S.P. REYNOLDS, "Transition to the Radiative Phase in Supernova Remants", *Ap. J.*, **500,** 10 June, p.342, (1998).

[3] KEITER, P.A. et al., "Observation of a Hydrodynamically-Driven Radiative-Precursor Shock", *Phys. Rev. Lett.*, **89,** 165003/1, (2002)

[4] BOZIER, J.C. et al., "Experimental Observation of the Radiative Wave Generated in Xenon by a Laser Driven Supercritical Shock", *Phys. Rev. Lett.*, **57,** 11, p. 1304, (1986).

[5] KOENIG,M. et al., "Radiative Shock Experiment Using High Power Laser", AIP Conf. Proc., **620**, 1, p.1367, (2002)

[6] EDWARDS, J.M. et al., "Investigation of Ultrafast Laser-Driven Radiative Blast Waves", *Phys. Rev. Lett.*, **87,** 8, 0850041 (2001)

[7] SHIGEMORI, K., et al., "Developing a Radiative Shock Experiment Relevant to Astrophysics", *Ap. J.*, **533**, L159, (2000)

[8] VISHNIAC, E. and D. RYU, "The Dynamic and Gravitational Instabilities of Spherical Shocks", *Ap. J.*, **274,** p. 152 (1983).

[9] VISHNIAC, E. and D. RYU, "On the Stability of Radiating Shocks", *Astrophysical Journal*, **337**, p. 917 (1989).

[10] GRUN, J. et al, "Instability of Taylor-Sedov Blast Waves Propagating Through a Uniform Gas", *Phys. Rev. Lett.*, **66**, 21, p.2738 (1991).

[11] LAMING, J.M. and J. GRUN, "Dynamical Overstability of Radiative Blast Waves: the Atomic Physics of Shock Stablity", *Phys. Rev. Lett.*, **89,** 12, 125001 (2002).

[12] FORSMAN, A.C. and G.A. KRYALA, "Non-Doppler Shift Related Experimental Shock Wave Measurements Using Velocity Interferometer Systems for Any Reflector", *Phys. Rev. E.,* **63,** 056402 (2001).